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Assessment of future scenarios for wind erosion sensitivity changes based on ALADIN and REMO regional climate model simulation data

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Abstract: The changes in rate and pattern of wind erosion sensitivity due to climate change were investigated for 2021–2050 and 2071–2100 compared to the reference period (1961–1990) in Hungary. The sensitivities of the main influencing factors (soil texture, vegetation cover and climate factor) were evaluated by fuzzy method and a combined wind erosion sensitivity map was compiled. The climate factor, as the driving factor of the changes, was assessed based on observed data for the reference period, while REMO and ALADIN regional climate model simulation data for the future periods. The changes in wind erosion sensitivity were evaluated on potentially affected agricultural land use types, and hot spot areas were allocated. Based on the results, 5–6% of the total agricultural areas were high sensitive areas in the reference period. In the 21st century slight or moderate changes of wind erosion sensitivity can be expected, and mostly 'pastures', 'complex cultivation patterns', and 'land principally occupied by agriculture with significant areas of natural vegetation' are affected. The applied combination of multi-indicator approach and fuzzy analysis provides novelty in the field of land sensitivity assessment. The method is suitable for regional scale analysis of wind erosion sensitivity changes and supports regional planning by allocating priority areas where changes in agro-technics or land use have to be considered.

Keywords: wind erosion sensitivity projection; regional climate model simulations; fuzzy analysis; hot spot analysis

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1 Introduction

Wind erosion in Europe affects large areas; about 42 million ha of European agricultural lands may be affected by wind erosion [1]. Large areas are influenced in the semiarid areas of the Mediterranean region [2, 3], in the temperate climate areas of the northern European countries [4, 5] or in the Carpathian Basin [6, 7]. Over the past decades, the significance of the wind erosion problem is increased because of the changing agricultural practices (*e.g.* increase in the size of fields, the intensive use of machinery or removal of hedgerows) [8] and further increase can be expected due to the projected climate change [9–11]. Therefore, it is important to delineate more precisely the location and the rate of this hazard at present and also in the next decades. Research increasingly focus on wind erosion at plot scale and also on regional scales [12].

Wind erosion and the rate of its damage are determined by several factors (*e.g.* soil parameters, lithology, climate, vegetation, anthropogenic effects) [13, 14]. Bagnold [15] determined a relation for the calculation of wind erosion using these factors. Later it was improved by a wind erosion equation (WEQ – Wind Erosion Equation and RWEQ – Revised Wind Erosion Equation), and other models were also developed (*e.g.* WEPS – Wind Erosion Prediction System, AUSLEM – AUStralian Land Erodibility Model) [16–22]. These models were designed in plot scale using field measurements and empirical knowledge; however, they work with several limiting factors (*e.g.* wind fetch length, roughness of soil surface) [23]. These approaches are typically process-based models, however, the applied mathematical and physical relationships cannot be simply scaled up to regional applications [22]. Regional

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scale methods are problematic, because of the spatial validity, however there are several attempts to develop more accurate regional scale estimations [24–27].

Wind erosion and the accompanying sediment accumulation cause huge agro-economic damages in the Carpathian Basin. Agricultural loss due to wind erosion results from direct impacts (physical damage on crops, mostly vegetables and sugar beet in April) that potentially affects smaller areas (15–20.000 hectares) in a value of 1500–3000 EUR/ha. However the estimation of loss is difficult due to the lack of information about damages, since insurance exists only for sand-blast damage up to 0.5–2% of the crop value, mostly bought by vegetable farmers on sand land regions [28]. Indirect impacts are more significant (*e.g.* degrading soil structure and fertility, decrease of the production area, and increased costs of labour, chemicals, seeds and maintenance), but they can not be easily quantified [29]. Natural hazards altogether (hail, wildfire, spring frost, drought, excess water, heavy precipitation, wind erosion) caused around 300 million EUR financial loss in the last decade [28, 30]. Based on the potential wind erosion hazard map 26.5 percent of the territory of Hungary is highly and moderately endangered by wind erosion risk [31]. The experienced decrease of precipitation during the spring months, with a rate of a nearly 20% between 1901 and 2010 has contributed to the increase of wind erosion hazard [32].

Regional scale wind erosion hazard maps are available for Hungary, most of them take into consideration only physical soil properties and critical wind speed for the calculation [6, 33, 34]. An integrated regional-scale wind erosion sensitivity map was also calculated using GIS and fuzzy analyses based on soil parameters, land cover, climatic conditions and land use to estimate the regional differences in wind erosion sensitivity and exposure in Hungary [35]. Regional scale is suitable for environmental, landscape or spatial planning applications of agricultural and environmental programs and strategies [36]. In the viewpoint of planning, it is crucial to deal with the management of hazards and to allocate those places where increasing wind erosion risk can be expected.

In the article temporal and spatial alterations in wind erosion senisitivity due to the impact of climate change were investigated based on climate model simulation data compared to the reference period (1961–1990). The key questions were:

1. how the rate, spatial pattern and distribution of wind erosion sensitivity were projected to change in the study area, the agricultural areas of Hungary;
2. how the extent of the areas with different sensitivity was projected to change until the end of the 21st century (2021–2050, 2071–2100 compared to 1961–1990) when integrating and comparing the two regional climate change simulations of REMO [37] and ALADIN [38];
3. what regional tendencies can be found in the extent of the most sensitive areas (increase, no change, decrease of sensitivity) in the case of different land cover types?

2 Materials and methods

2.1 Study area

The investigated area, Hungary is located in SE Europe in the Carpathian Basin, approx. 68% of which is covered by agricultural areas (Fig. 1). The area is determined by a yearly mean precipitation of 500–750 mm and an average temperature of 10–11°C. The countrywide yearly average wind speed is 2–4 ms^{-1}, the monthly averages are highest in the spring period (March and April) [39]. The number of days on which the maximum wind speed is over 10 ms^{-1} is also the highest in April [40]. The main wind direction above 5 ms^{-1}, which is important in inducing erosion, is north-west [41]. The surface of the investigated areas is mostly covered by sediments of fluvial, lacustrine, aeolian origin, resulting in a various soil cover. Loamy sediments cover most of the areas, however, sand covered territories are also in a huge extent (Fig. 1).

2.2 Data

For analysing wind erosion sensitivity in regional scale, where local parameters cannot be assessed, the most relevant environmental parameters are soil texture properties, vegetation cover and climate parameters [14, 15], thus these factors were calculated in this assessment.

The soil and vegetation factors were evaluated by using the calculation method of the regional scale wind erosion sensitivity map of Mezősi *et al.* [35]. In the calculation to analyse soil sensitivity [35], the soil erodibility index [19] was assessed by using the soil texture categories of the Hungarian Agrotopographical map [42] and to analyse the effect of vegetation cover NDVI values were calculated [43] for the most important spring period (March-April) on the basis of MODIS remote sensing data, because the vegetation on the cultivated fields have little cover to

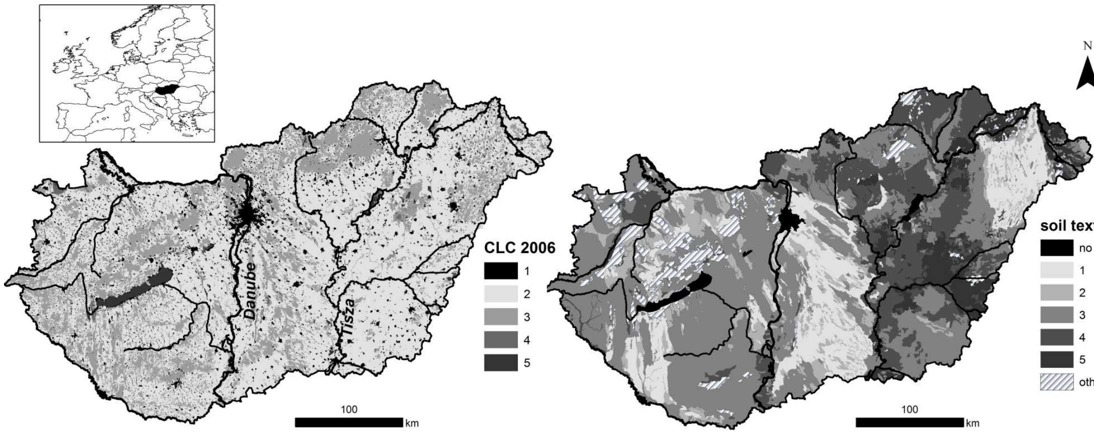

Figure 1: Main land cover types [45] and soil texture classes of the study area [42]; land cover: 1: artificial surfaces; 2: agricultural areas; 3:Forests and semi-natural areas; 4: wetlands; 5: water bodies); soil texture: 1: sand; 2: loamy sand; 3: loam; 4: loamy clay; 5: clay.

protect the soils in this spring (March-April) period. To calculate the climate parameters for the reference period (1961–1990) observed monthly precipitation, monthly average temperature, and monthly average wind speed in March and April (source: Hungarian Meteorological Service) were used. The soil moisture and vegetation cover are usually low and monthly average wind speeds are the highest during these spring months (March–April); therefore, wind erosion can be especially active at this time of the year.

The projected future changes of the climate parameters were analysed using two regional climate models, REMO and ALADIN with a spatial resolution of 0.22° (approximately 25 km). These models utilise the A1B scenario to model anthropogenic climate forcing, which represents an average development of greenhouse gas emissions [44]. The climate projections were generated by the Numerical Modelling and Climate Dynamics Division of the Hungarian Meteorological Service. These model simulations provided daily data about the changes of temperature and precipitation and monthly wind speed data for the periods 2021–2050 and 2071–2100 with respect to the reference period of 1961–1990. From all of these data, monthly average values were calculated and evaluated for the two future periods.

To allocate the area, potentially affected by wind erosion on land use basis, CORINE Landcover 2006 map (CLC) [45] was used (Table 1).

2.3 Methods

2.3.1 Calculation of climate-factor

The climate parameters were assessed by calculating the climatic factor of Wind Erosion Equation WEQ [46–49] for the most relevant spring period of the year (March-April). The calculated index of climatic factor uses monthly temperature (T), monthly precipitation (p) and monthly average wind speed data.

Calculation of climate (C) factor (1) [46–48]:

$$C = \frac{386 \cdot u^3}{PE^2} \tag{1}$$

where u: average monthly wind speed (m/s), PE: Thornwaite precipitation-effectiveness index (2)

$$PE = 3.16 \cdot \sum \left[\frac{Pi}{1.8 \cdot {}^*Ti + 22} \right]^{\frac{10}{9}} \tag{2}$$

where Pi: monthly precipitation (mm), Ti: monthly average temperature (°C)

With this calculation method, average values were calculated for the reference period (1961–1990) based on observed meteorological data and to assess the future changes of wind erosion hazard the changes of the climate factor were applied for the two future period (2021–2050 and 2071–2100) on the basis of the ALADIN and REMO regional climate model simulation data. The behaviour of the applied models is complex, having uncertainties, however, based on the validation studies, these models can be efficiently used for climate research purposes [50–53].

Table 1: The used datasets during the analyses and their sources.

Indicator	Used data	Spatial resolution	Source
sensitivity of soil	soil erodibility index from the Hungarian Agrotopographical Map	250 × 250 m	[27]
sensitivity of vegetation	vegetation cover from NDVI	250 × 250 m	[27]
sensitivity of climate (wind, precipitation and temperature data were used)	C factor	250 × 250 m	ALADIN and REMO RCMs data for 2021–2050 and 2071–2100 (Meteorological information services, Hungary), observed data for 1961–1990 (Meteorological information services, Hungary)
land cover (~land use)	Agricultural classes: 211 Non-irrigated arable land 221 Vineyards 222 Fruit trees and berry plantations 231 Pastures 242 Complex cultivation patterns 243 Land principally occupied by agriculture, with significant areas of natural vegetation	~100 × 100 m	[34]

2.3.2 Calculation of sensitivity maps

To calculate the sensitivity of wind erosion, it is necessary to identify the basic relationships between the rate of wind erosion and the relevant affecting factors (soil texture properties, vegetation cover and climate factor).

Sensitivity was calculated separately for the influencing factors by using fuzzy analysis [54–56] and using these sensitivity values, a combined sensitivity map was compiled (Fig. 2). The fuzzy relations can be easily incorporated into geographic information systems (GIS) and the sensitivity values can be calculated on pixel basis, therefore it is effective for comparing the results with other sites [57].

For the calculation of the sensitivity of the affecting factors IDRISI software was used. In this software the relation between two parameters is described by fuzzy membership functions. The fuzzy membership function can be linear, exponential, logarithmic or polynomial [**?**].

In case of soil texture properties, the increasing experimental t ha^{-1} yr^{-1} erosion value of the soil means that the sensitivity is also increasing [58, 59]. The applied fuzzy membership function describing the relationship between the soil texture properties and the rate of wind erosion was exponential and monotonically increasing. In terms of vegetation, the increasing vegetation density causes ex-

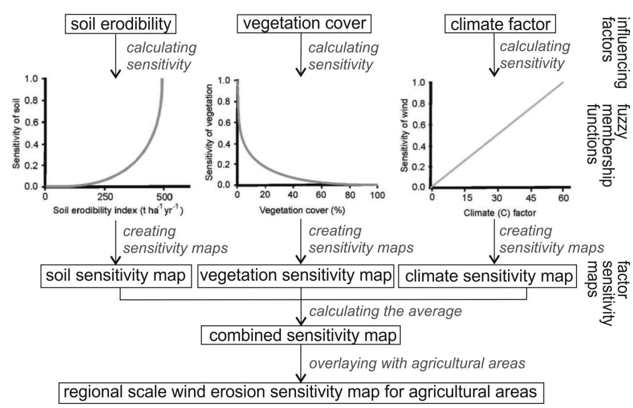

Figure 2: Flowchart of the applied methodolical framework.

ponential reduction of the sensitivity of wind erosion [60]. Consequently, the applied fuzzy membership function was exponential and monotonically decreasing [35]. The relationship between the C factor and the rate of wind erosion is linear, thus the applied fuzzy membership function was linear and monotonically increasing [49, 59, 61]. This means that the increase in the C factor resulted in the increase of the wind erosion sensitivity in the area (Fig. 2).

The overall sensitivity was calculated by averaging the separate factor sensitivity maps to a combined sensitivity map to avoid the problem of weighting. Thus, in the final sensitivity assessment, each factor was given an equal

Table 2: CORINE Land Cover (CLC) nomenclature for agricultural areas.

Level 1	Level 2	Level 3	Area (km^2)
2. Agricultural areas	21 Arable land	211 Non-irrigated arable land	48957
	22 Permanent crops	221 Vineyards	1464
		222 Fruit trees and berry plantations	804
	23 Pastures	231 Pastures	6425
	24 Heterogeneous agricultural areas	242 Complex cultivation patterns	2446
		243 Land principally occupied by agriculture, with significant areas of natural vegetation	1456

weight. Using the method of Mezősi *et al.* [35], wind erosion sensitivity was calculated by fuzzy analyses, where 0 means not sensitive at all, 1 means the maximum sensitivity. For example 0.25 means that the sensitivity is 25%, thus the area is rather not sensitive than sensitive.

Based on the detailed sensitivity map, to assess the summarized sensitivity in a more comprehensible way, it is inevitable to categorize the sensitivity as high sensitivity, medium sensitivity and low sensitivity. However there are no well-defined threshold values between the categories and it is hard to define which exact sensitivity value should be used in the assessment. In this study, the following thresholds for wind erosion sensitivity classes were used: high sensitivity over 0.35, medium sensitivity 0.2–0.35 and low sensitivity below 0.2. These threshold values were intrinsically arbitrary; however the thresholds were adjusted to the experimental wind erosion rates,field survey results and recorded economic losses [35].

To carry out the temporal analysis, the sensitivity map for the reference period (1961–1990) was compared to the estimated future wind erosion sensitivity maps. In the analysis of future changes in wind erosion sensitivity, the soil factor and the vegetation factor were fixed, because the soil is considered as invariable in this time period, while the natural changes of the vegetation is very slow, however land use can be modified by anthropogenic activities, therefore the long-term projection of vegetation alteration is difficult. Thus, in the modelling of the two future periods the driving factor of the changes is the climate factor. Consequently to assess the future changes, the observed meteorological data for climate factor was replaced by the simulation data of the ALADIN and REMO climate models, while soil and vegetation factors were the same as it was in the reference period.

Based on the results of fuzzy analysis, hot spot areas were allocated for March and April separately where all of the soil, vegetation, present and future climate sensitivity were higher than 0.35. These high sensitivity areas are the most exposed to the investigated natural hazard both at present and in the future.

2.3.3 Linking of wind erosion sensitivity to agricultural land uses

In the spring period the used NDVI vegetation index is usually low for every land cover class; therefore, it is difficult to distinguish the different land use types (*e.g.* agricultural areas, forests or built-up areas), however, wind erosion does not typically occur in forests or urbanised areas. Therefore, land cover type was also employed in the analysis to locate the potentially affected areas. By the help of the CORINE Landcover 2006 map, agricultural areas were selected (CLC 211, CLC 221, CLC 222, CLC 231, CLC 242, CLC 243 – Table 2), because on these areas the vegetation cover opens and closes on annual and seasonal schedules according to the agricultural crop rotation and these areas are exposed to wind erosion in the early spring period. Therefore, the combined sensitivity to wind erosion was calculated for the agricultural areas of CORINE land cover classes. For each land cover class the Number of patches (pcs), Area (km^2), Number of high sensitive (0.35–1.00) patches (pcs), Area of high sensitive patches (km^2) and Ratio of high sensitive areas (%) in March and April were assessed. To analyse future tendencies in wind erosion sensitivity on different land cover types, the changes of the area of the high sensitivity category (wind erosion sensitivity higher than 0.35) were analysed for the two future periods.

3 Results and discussion

3.1 Climate sensitivity based on regional (climate model) simulation

Based on the calculation of climate sensitivity for the period of 1961–1990, the highest values can be observed in the north western and in the centre part of the study area in March (Fig. 3). In April, slightly higher values were found in the whole study area compared to March with similar spatial pattern. For the period of 2021–2050 based on the ALADIN model simulation the value of climate factor was expected to decrease on most of the areas in both March and April, indicating the reduction of climate sensitivity, but the decrease was slighter in April. The changes of the climate factor showed contradictory results on the basis of REMO model simulation, since they estimated an increase in the north-western and the south-eastern parts. The increase had a higher rate in April. This significant difference between the results were mainly caused by the different precipitation projection of the models in March and April.

In longer time scale (2071–2100), the increase of the climate factor can be expected compared to the 1961–1990 period on most of the area. Higher increase was projected in the north-western and south-eastern parts of the study area in both March and April. Compared to the period of 2021–2050, the values of the climate factor for 2071–2100 were projected to decrease on the basis of REMO model simulation in both March and April, while ALADIN indicated increase in the climate factor in both months. The pattern of the climate sensitivity seemed to be unchanged in both shorter and longer time scale.

The applied climate simulations have uncertainties arisen from the modelling method and the natural climate variability. Moreover, modelling the social and economic changes in the future (meaning the anthropogenic climate forcing factor in the models) is the most difficult and therefore, the most uncertain part of the models [10, 62]. To evaluate the uncertainty and validate the model results several studies were carried out, which confirmed the applicability of the models for climate research purposes [50–53]. Based on the model validations for the Carpathian Basin spring temperature is quite reliable based on REMO, although it is underestimated by ALADIN. In the case of precipitation both model validations result in overestimation in the study area [51, 52]. Since both temperature and precipitation bias can lessen wind erosion potential, the estimations of future wind erosion sensitivity possibly underestimate the potential increase and overestimate the potential decrease. Wind parameter values are hardly quantifiable in climate models, however, it is possible to derive development trends from the future simulations [63].

In this study data of two regional climate model were applied and compared and the results differ slightly from other multi-model approaches [64]. 30-year-averages were calculated according to the climatological practices that can provide efficient practical information for decision makers [23].

3.2 Wind erosion sensitivity assessment

The integrated sensitivity analysis on agricultural lands in March and April (Fig. 4) allocated areas, where high wind erosion sensitivity was characteristic for the 1961–1990 period. It corresponded to the spatial pattern of soil texture classes (see Fig. 1). The highest sensitivity (fuzzy value > 0.35) values occurred in the sandland regions of the study area covered by fluvio-aeolian loss and sand. Between sensitivity maps for March and April, there was no significant difference in the extent of high sensitivity areas, only a slight difference in the extent of medium sensitivity areas occurred.

For the future period of 2021–2050 REMO and ALADIN simulations indicated different tendencies. Based on ALADIN simulation, decrease in the extent of medium sensitivity areas could be expected in March, especially in the western part of the study area and the extent of high sensitivity areas were also projected to decrease. Similar trends were projected in April, but to a smaller rate. REMO simulation based sensitivity calculation did not show significant changes on the western part, but on the south-eastern part of the country higher changes were indicated and the tendency was increasing. REMO simulation based sensitivity calculation projected high increase of wind erosion sensitivity in both months and the territorial expansion of high sensitivity areas was projected. In April, almost the whole study area, except for the northern territories, were characterised by medium or high sensitivity in the 2021–2050 period based on REMO data. The northern territories were less affected at present and in the future as well.

For the period of 2071–2100, increasing wind erosion hazard in March was indicated using ALADIN simulation data, on the south-eastern part of the study area compared to the previous investigated period. Based on REMO simulation, a decreasing extent of the medium sensitivity areas in both March and April was projected, mostly in the western part of the study area, however, it was not so significant and showed a more fragmented pattern compared to the previous period. Despite the decreasing trend between the periods of 2021–2050 and 2071–2100 the area

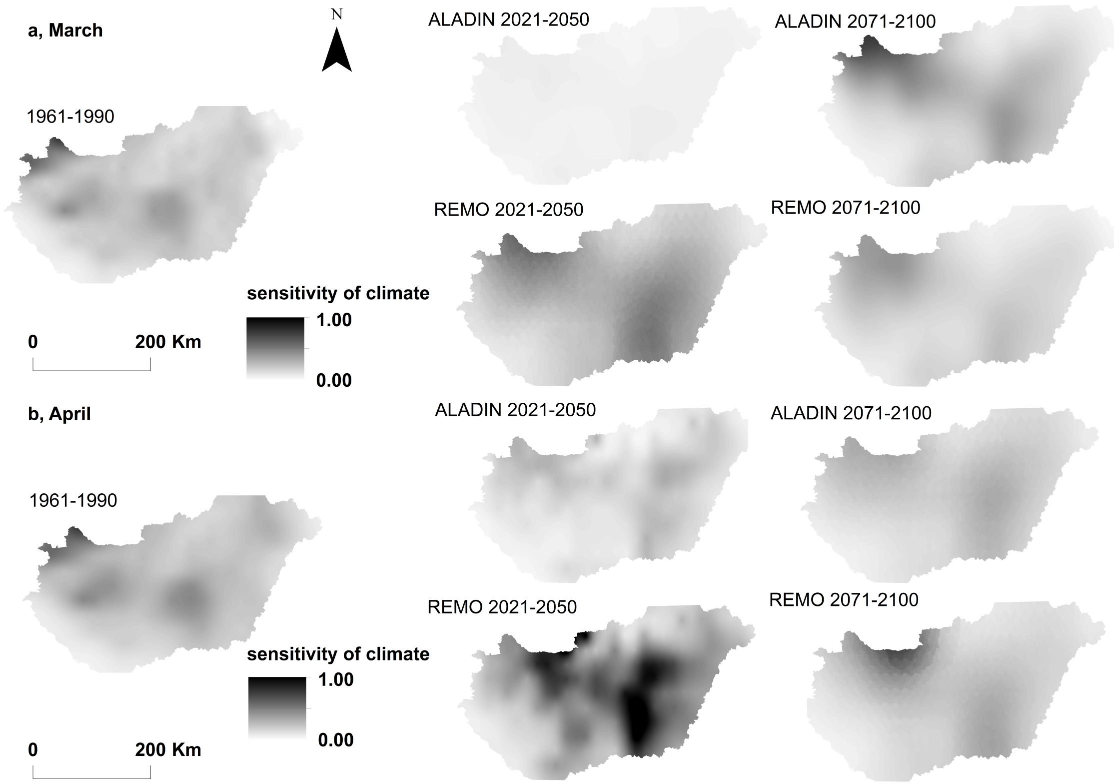

Figure 3: The climate sensitivity (C-factor) in March and April in the period of 1961–1990, 2021–2050 and 2071–2100 based on ALADIN and REMO climate model simulation data.

of high and medium sensitivity areas was projected to be even higher than it was in the reference period (1961–1990) in the centre part of the country.

Based on the results, moderate change of wind erosion sensitivity was expected in the 21st century due to the impact of climate change. The applied climate model simulations, the ALADIN and REMO showed differences in rate and pattern of wind erosion hazard for the modelled future periods. Especially for the first period the rate and also the direction of the changes were different, thus definite tendencies could hardly be drawn. For the period of 2021–2050 on the basis of REMO simulation the extent of ‘high sensitivity areas’ and also the ‘medium sensitivity areas’ increased, while ALADIN simulation data indicated decrease in both sensitivity categories (Fig. 5). For the period of 2071–2100, only minor changes of the extent of the ‘high sensitivity’ and also ‘medium sensitivity’ areas were projected on the basis of both model simulations compared to the reference period in March and also in April, however the rate of increase was different in the two months and according to the two models. This difference between the results were mainly caused by the different precipitation projection of the models in the spring period (March and April).

The hotspot analysis allocated the areas, which were the most exposed to the investigated natural hazard at present and also in the future (Fig. 6). In March an area of 445 km^2 was allocated as hot spot of high wind erosion sensitivity, especially in the centre part of the Danube-Tisza Interfluve. In April not only the aforementioned area, but also some parts of Nyírség were indicated as hot spots in a total extent of 975 km^2. Based on the two climate model simulation data, very similar results in the pattern and extent of the hotspot areas were arisen.

Estimating wind erosion hazard is a major challenge due to the limited calculation methods for larger areas [36]. The active and passive prevention and adaptation practices can influence the factors playing role in wind erosion. In the viewpoint of climate, one of the key factors is the wind speed that can be modified by shelterbelts or by the increase of surface roughness (*e.g.* by agro-techniques or vegetation cover) [65–67]. In the viewpoint of soil the increase of the soil aggregates or soil covering by manure or straw can be a good solution. However, these modifications are local interventions relevant for plot scale and they slightly have impact on regional wind erosion pattern.

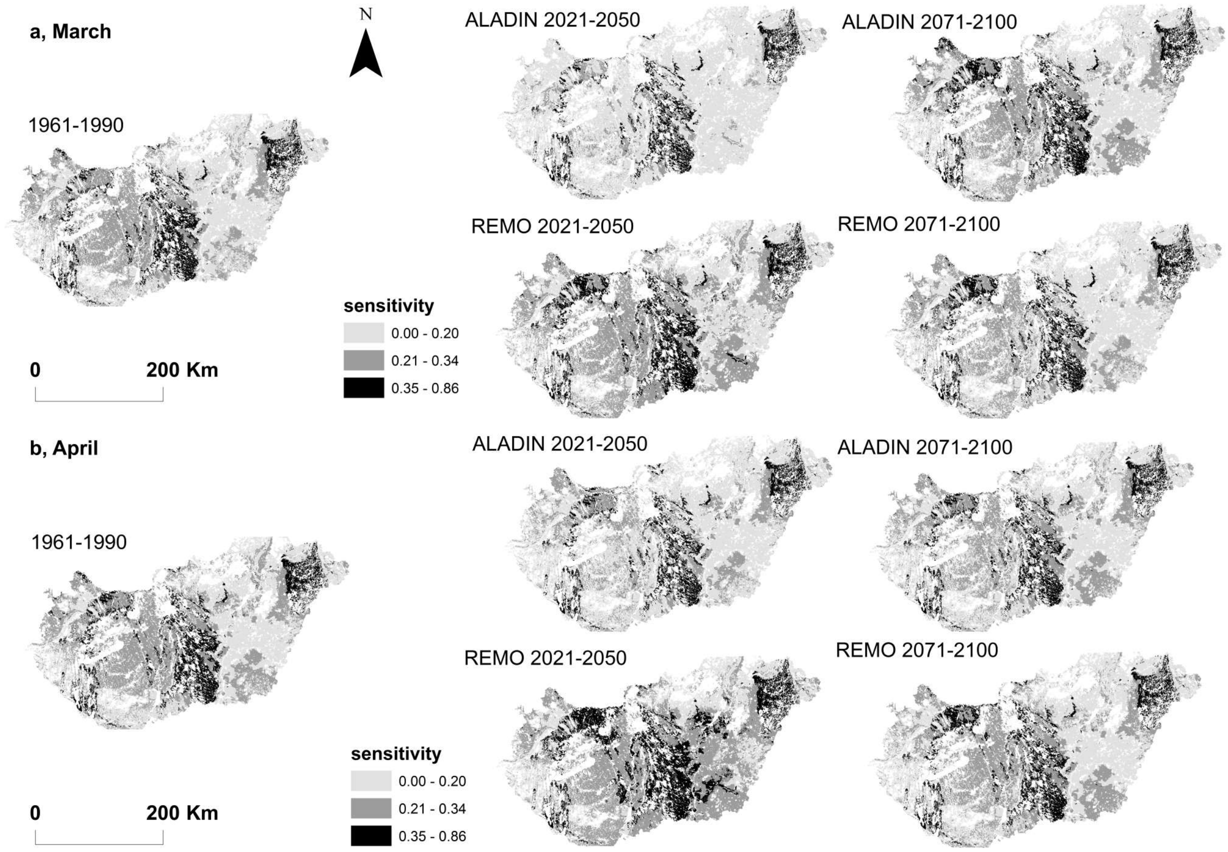

Figure 4: Wind erosion sensitivity of the agricultural lands in March and April for the period of 1961–1990, 2021–2050 and 2071–2100 based on soil, vegetation and climate sensitivities.

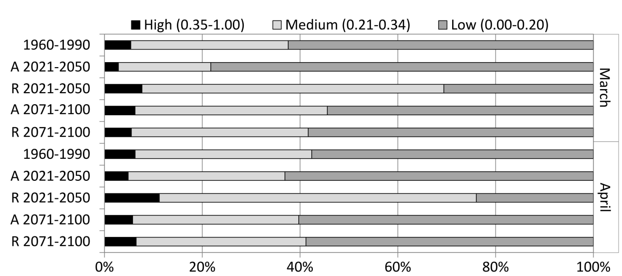

Figure 5: Area (% compared to the total extent of the agricultural areas) of wind erosion sensitivity classes in the periods of 1960–1990 and 2021–2050, 2071–2100 based on REMO (R) and ALADIN (A) regional climate model simulation data

3.3 Wind erosion sensitivity in March and April by land use

Wind erosion sensitivity was analysed according to different agricultural land cover classes of CORINE for the reference period (1961–1990) to reveal the differences in sensitivity between the land use classes. The calculated sensitivity values for April were slightly higher in case of all land cover types (Table 3) compared to March. The highest sensitivities were shown by the vineyards (CLC 221), the fruit tree and berry plantations (CLC 222) and the complex cultivation patterns (CLC 242), where more than 25% of their areas considered as high sensitive. 5–10% of the non-irrigated arable lands, pastures and land principally occupied by agriculture with significant areas of natural vegetation were defined as high sensitive. Although the ratio of the high sensitive areas of non-irrigated arable land was only 2–4%, the extent of the high sensitivity area in this land cover type was higher than in all the other classes'.

The future wind erosion sensitivity was assessed on the basis of climate model simulations assuming invariable land use pattern. The two climate models in the 2021–2050 period showed different rate and direction in the changes of the extent of high sensitivity patches in case of all CORINE land cover types (Table 4). The ALADIN based calculation showed decrease in all categories for the 2021–2050 period, and the highest decrease could be observed in case of CLC 211 and CLC 231. Smaller decrease (by 9–30%) of the high sensitivity areas was projected for April. However, REMO based calculation projected increase of the high sensitivity areas in all land cover classes, and the

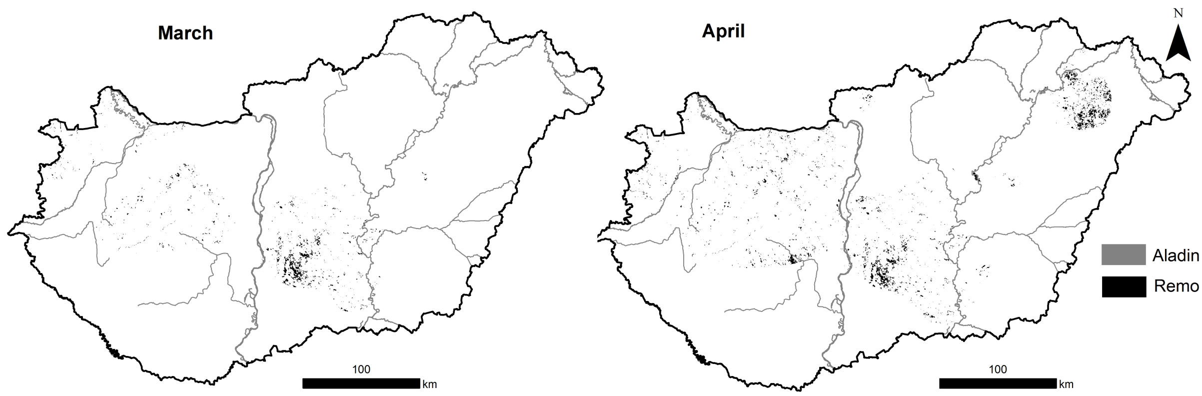

Figure 6: Hot spot areas of wind erosion sensitivity for March and April based on the REMO and ALADIN climate simulation data.

highest increase was expected in case of CLC 243. Based on REMO simulation higher differences between the two months (March and April) were identified.

The longer-term projections for the 2071–2100 period did not show significant differences compared to the reference period (1961–1990) in March, the changes were mostly below 15% (from −2% to +39%). Calculations based on ALADIN showed increase in the area of high sensitivity patches in all land cover classes in March; REMO based calculations projected minor decrease in case of CLC 221 and CLC 222. For April, only two land cover types (CLC 242, CLC 243) showed increase (3–25%) in the extent of the high sensitivity areas based on ALADIN, while the rate and direction of changes were different on the basis of REMO simulation, the extent of the high sensitivity areas showed increase except of CLC 211 and CLC 222.

The results show that for the period of 2071–2100 both models project only minor changes in the extent of the high sensitivity and also the extent of medium sensitivity areas compared to the reference period in March and also in April. However, remarkable differences can be detected between the different agricultural land use types, confirmed also by the findings of Tibke [68], Gomes *et al.* [12], Leenders *et al.* [69], or Horel *et al.* [70], who identified that the different agricultural land use and techniques can have a significant effect on wind erosion hazard. To detect tendencies, considered as important in case of the different land use types, averaged data of the two models was considered, where more than 5% area change was considered as important change (Table 5). Increasing tendency in the sensitivity was identified in case of 'Pastures' (CLC 231), 'Complex cultivation patterns' (CLC242) and 'Land principally occupied by agriculture, with significant areas of natural vegetation' (CLC 243) based on the model results. These land use types are more favourable from the viewpoint of wind erosion than intensively cultivated land use types (*e.g.* arable land). Future land management planning should aim to avoid the increase of cultivation intensity in these areas. No noticeable changes in wind erosion sensitivity can be detected on "vineyards" (CLC 221) and "fruit trees and berry plantations" (CLC 222), but more than 30% of these areas have already high sensitivity. In case of arable lands (CLC211) the projected tendency is indefinite. For the first period, model simulation data showed wind erosion sensitivity decrease in the early spring period (March), but increase in April, while for 2071–2100 the data showed contrary tendencies. Since arable lands cover the largest area, the areas possibly affected by increasing tendency are the largest in spite of the less clear tendency. On areas where increasing tendency can be expected on arable lands, the highest attention from future planning and adaption is, required. Land cover change can also be a good possibility, however, only in case of less-favourable soils (*e.g.* from CLC 211 to CLC 231, CLC 242 or CLC 243). The current analysis assumed invariable future land use pattern. Anthropogenic activities should modify land use considering regional sensitivity to mitigate possible wind erosion hazard.

4 Conclusion

Significant territories in the Carpathian Basin face high wind erosion sensitivity at present, and a slight increase of wind erosion hazard can be expected for the end of

Table 3: Wind erosion sensitivity according to CORINE land cover classes in the reference period 1961–1990.

CLC class	Number of patches (pcs)	Area (km^2)	Number of high sensitivity patches (pcs)	Area of high sensitivity patches (km^2)	Ratio of high sensitivity areas (%)
March					
211 Non-irrigated arable land	3821	48957.05	494	1397.15	2.85
221 Vineyards	1041	1464.45	233	441.32	30.14
222 Fruit trees and berry plantations	960	804.53	300	274.98	34.18
231 Pastures	6202	6425.40	592	485.82	7.56
242 Complex cultivation patterns	3337	2446.27	534	627.05	25.63
243 Land principally occupied by agriculture, with significant areas of natural vegetation	2920	1456.57	169	87.00	5.97
April					
211 Non-irrigated arable land	3821	48957.05	568	1709.41	3.49
221 Vineyards	1041	1464.45	256	461.60	31.52
222 Fruit trees and berry plantations	960	804.53	341	311.35	38.70
231 Pastures	6202	6425.40	700	575.75	8.96
242 Complex cultivation patterns	3337	2446.27	604	696.74	28.48
243 Land principally occupied by agriculture, with significant areas of natural vegetation	2920	1456.57	201	103.61	7.11

Table 4: The area and the percential changes of the high sensitivity areas according to CLC in March and April based on the the REMO and ALADIN climate model simulation data for the 2021–2050 and 2071–2100 periods.

CLC class			211	221	222	231	242	243
March								
Area of high sensitivity patches (km^2)		1961–1990	1397.15	441.32	274.98	485.82	627.05	87.00
Changes in the extent of high sensitivity areas (%)	ALADIN	2021–2050	−60.65	−25.07	−19.57	−56.29	−37.49	−48.21
	REMO		47.68	13.02	19.07	74.04	32.18	83.91
	ALADIN	2071–2100	14.75	6.53	1.06	32.96	15.38	39.19
	REMO		2.89	−1.93	−1.72	1.97	4.02	9.08
April								
Area of high sensitivity patches (km^2)		1961–1990	1709.41	461.60	311.35	575.75	696.74	103.61
Changes in the extent of high sensitivity areas (%)	ALADIN	2021–2050	−30.29	−15.73	−10.35	−28.56	−9.00	−19.94
	REMO		104.07	17.53	22.90	124.67	35.70	141.63
	ALADIN	2071–2100	−15.66	−6.50	−4.15	−5.33	3.41	7.98
	REMO		−1.14	2.07	−2.08	11.87	7.66	25.14

Table 5: Trends in the change of the extent of the high sensitivity areas to wind erosion according to CORINE patches based on averaged REMO and ALADIN climate model simulation data for the 2021–2050 and 2071–2100 periods (↑ - increase; ↓ - decrease; ~- no important change).

	Projection for 2021–2050		Projection for 2071–2100	
	March	April	March	April
211	↓	↑	↑	↓
221	↓	~	~	~
222	~	↑	~	~
231	↑	↑	↑	~
242	~	↑	↑	↑
243	↑	↑	↑	↑

the century based on ALADIN and REMO regional climate simulation data. Two main hot-spot areas were allocated where prevention or adaptation measures are of high importance. The most apparent finding was that the pattern of climate sensitivity in regional scale seemed to be unchanged in both shorter and longer time scale. The spatial analysis indicated that on the western part of the country the wind erosion sensitivity was expected to be more variable and the trends were more unclear than on the eastern part during the 21st century. Wind erosion hazard can be more significant than it was projected in this study, since environmental hazards can have a synergistic effect on each other. Owing to a drought period in summer, vegetation can perish to such an extent that soil surfaces can become uncovered and exposed to wind erosion; furthermore, the decreasing groundwater table can also enhance wind erosion sensitivity.

Despite of the discrepancies and uncertainties of climate simulations, some general aspects of the changes can be identified *e.g.* hot spot areas, which still could provide valuable information for spatial planning and land management purposes. The applied combination of multi-indicator approach and fuzzy analysis provides novelty in the field of land sensitivity assessment and the method is suitable for regional scale analysis of wind erosion sensitivity changes. The advantage of the applied fuzzy method in a land sensitivity assessment is the ability of soft computing, namely this tool permits modelling a system without detailed mathematical descriptions using qualitative as well as quantitative data [71]. Thus, this method is suitable for the ensemble assessment of the factors important in wind erosion, although the available datasets with different spatial resolution and quality do not allow the application of the detailed equations developed in plot scale. Regional scale data are necessary for regional planning to develop more focused strategies to allocate priority areas where changes in agrotechnics or land use have to be considered to make prevention and adaptation possible.

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